Journal of Infection and Public Health (2017) 10, 120—123

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Zika virus: Endemic and epidemic ranges of *Aedes* mosquito transmission

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Received 19 August 2016; accepted 8 September 2016

KEYWORDS
Geographic information systems;
Geographic information science;
Risk mapping;
Zika;
Aedes modeling

Summary As evidence linking Zika virus with serious health complications strengthens, public health officials and clinicians worldwide need to know which locations are likely to be at risk for autochthonous Zika infections. We created risk maps for epidemic and endemic *Aedes*-borne Zika virus infections globally using a predictive analysis method that draws on temperature, precipitation, elevation, land cover, and population density variables to identify locations suitable for mosquito activity seasonally or year-round. *Aedes* mosquitoes capable of transmitting Zika and other viruses are likely to live year-round across many tropical areas in the Americas, Africa, and Asia. Our map provides an enhanced global projection of where vector control initiatives may be most valuable for reducing the risk of Zika virus and other *Aedes*-borne infections.

Introduction

Zika virus is not a new infection [1]. The first known case of Zika was identified in a monkey in Uganda in 1947. Cases of the virus in humans were later identified in Uganda and Tanzania in 1948 [2]. Cases from many other countries in central and West Africa were reported between the 1960s and 1980s, and the virus was also found in Indonesia, Malaysia, Pakistan and Costa Rica. In 2009, an outbreak occurred on the island of Yap in the Federated States of Micronesia. In subsequent years, cases were recognized in several other Asian

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http://dx.doi.org/10.1016/j.jiph.2016.09.008
1876-0341/

and Pacific Island nations. In 2015, a large number of cases of Zika were diagnosed in Brazil, and cases began occurring in other countries within Central and South America and the Caribbean [1].

As the evidence linking Zika virus with serious health complications such as Guillain—Barré syndrome and microcephaly strengthens, public health officials and clinicians worldwide need to know which locations are likely to be at risk for autochthonous Zika infections [2]. This kind of location intelligence informs actions such as vector control strategies, public risk communications for disease prevention, and clinician training in diagnosis and response. At present, *Aedes* mosquitoes are considered to be the primary vectors of transmission for the Zika virus, particularly *Aedes aegypti* and *Aedes albopictus* [3]. In this paper, we use a variety of environmental and population datasets to identify locations where the habitat is suitable for *Aedes* mosquitoes to be present year-round or on a seasonal basis.

Methods

The goal of this analysis was to create an efficient, robust, and high resolution (1 km × 1 km) global analysis of Zika risk by creating a map of suitable environments for *Aedes* mosquitoes. To this, we (1) conducted a review of the dengue literature to identify the social and environmental factors most strongly associated with *Aedes*-borne infections such as Zika, chikungunya, dengue, and yellow fever [4], (2) acquired map layers for all five parameters that the literature search revealed were the best predictors of areas where mosquitoes are known to be present, and then (3) used ArcGIS Predictive Analysis Tools to map the places that are most suitable for Zika outbreaks.

For seasonal *Aedes* suitability, the literature review identified as the most suitable locations (1) elevation below 1800 m; (2) precipitation levels allowing mosquitoes to survive and breed; (3) annual mean temperature between 10 °C and 30 °C; (4) land cover that excludes areas that are barren, covered with permanent snow or ice, or bodies of water; and (5) a population density of greater than 0 people, since humans must be present in a place for it to be a risk zone for human Zika infections [4]. For mapping year-round suitability for *Aedes* mosquitoes, the minimum temperature of the coldest month had to be above 10 °C and the other four criteria remained unchanged. This change in temperature suitability narrowed the possible areas where *Aedes* mosquitoes could survive throughout the year and gave a clearer picture of which locations globally have the greatest potential to become endemic for *Aedes*-borne diseases [5].

Spatial data sources with global coverage were identified for each of the key parameters: (1) elevation from the WorldClim (publically available) database version 1.4 (release 3) [6]; (2) annual precipitation, the precipitation of the wettest and driest months, and the precipitation of the wettest, driest, and coldest quarters from WorldClim [6]; (3) annual mean temperature, the mean of the difference between the monthly maximum and minimum temperatures, the standard deviation of mean temperatures by quarter, the maximum temperature of the warmest month, the minimum temperature of the coldest month, and the mean temperature of the warmest quarter from WorldClim [6]; (4) 2009 land cover data from the ESA 2010 and UCLouvain Team (publically available) [7]; and (5) 2011 data on human population density from Oak Ridge National Laboratory's LandScan Database (available to researchers upon request) [8]. Additional details about these spatial datasets and the process for selecting key variables are available elsewhere [4].

The ArcGIS Predictive Analysis Tools Add-In (PA Tools), a free add-on to ArcGIS available from Esri (Redlands, CA) since 2014 [9], was used to identify all the locations globally where the elevation, precipitation, temperature, land cover, and population density characteristics were similar to the places where previous outbreaks of *Aedes*-borne infections have occurred. The Query Expression Editor within the PA Tools classified each location as having zero to five of the five key risk factors for Zika (altitude, temperature, precipitation, land cover, and population density) were present. Each location was classified on a scale from not suitable (0 parameters present) to highly suitable (all 5 parameters present). The adaptable analysis within the geographic user interface for PA Tools allowed for immediate visualization of how various inputs affect the suitability model, and the values for each parameter could be analyzed individually.

As a validation check, we compared our results with historic data (1960 through 2014) about *Aedes* locations from the Dryad digital repository [10]. This congruence provided face validity for the map we created from our literature search. While historic data on mosquito locations have been critical for past risk mapping efforts, they are not sufficient on their own to illustrate where Zika could occur today or in future years. First, there is no database of locations were *Aedes* are known to be absent, so sites not included in the database cannot necessarily be assumed to be *Aedes*-free. Also, since the range for these mosquitoes is expected

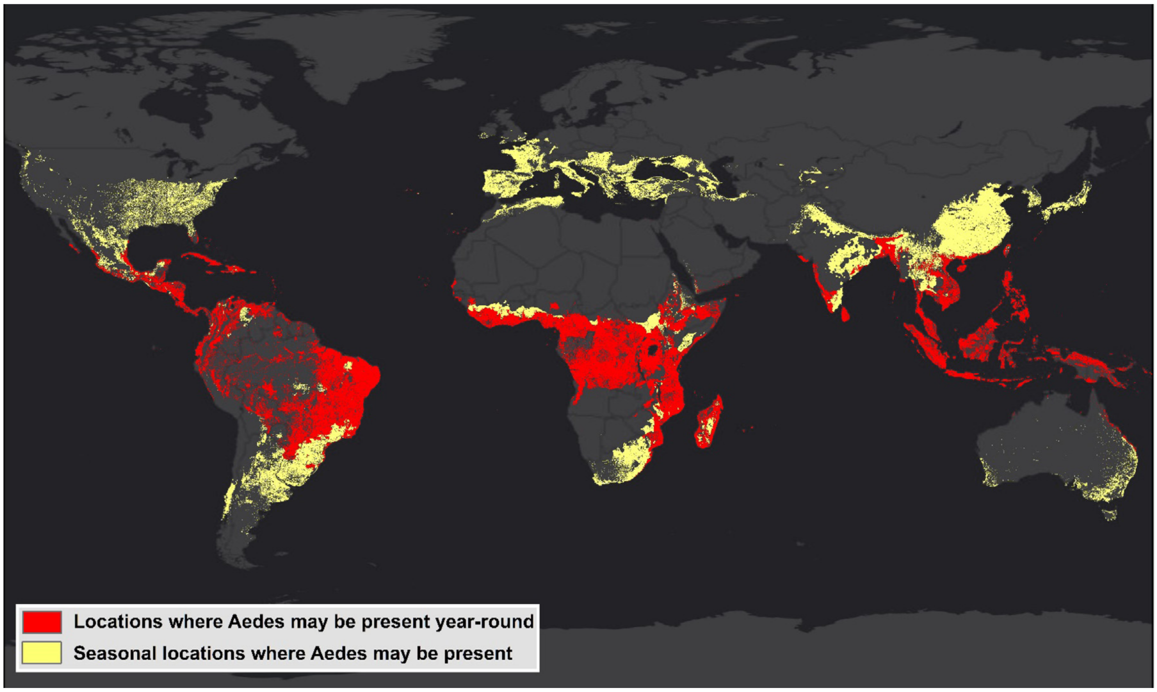

Figure 1 Global map of the locations suitable for seasonal presence (yellow) and year-round presence (red) of hematophagous *Aedes* mosquitoes.

to shift as climate changes occur, the past absence of mosquitoes would not be sufficient evidence of present absence. Our mapping methods overcomes both of those barriers. Importantly, this methodology does not require GIS expertise to implement, it does not require variables to have normal distributions or meet other assumptions of regression models, and the raster-based approach allows for the rapid identification of the locations most likely to be at high risk of environmentally-associated outbreaks so that prevention and control measures can be quickly implemented.

Results

Based on this suitability mapping technique, *Aedes* mosquitoes capable of transmitting Zika and other viruses are likely to live year-round across much of Central America, the Caribbean, and northern South America; most of coastal West Africa, central Africa, coastal East Africa, and Madagascar; parts of coastal India and southeast Asia, Indonesia, Malaysia, and the Philippines, and many Pacific Island nations (Fig. 1). Seasonal transmission is possible in a significantly larger area, including much of the southeastern United States and northern Mexico as well as some parts of southern South America, such as the Chilean coast; much of southern Europe and parts of North Africa; the southeast coast of Africa; much of South Asia and East Asia, including significant portions of China, Korea, and Japan; and parts of Australia and New Zealand.

Discussion

Suitability mapping methods are helpful for quickly identifying the places likely to have the greatest risk for various outbreaks so that resources can be allocated to the locations with the most urgent need for health education, vector control, and other prevention and control interventions. The maps for Zika can be efficiently updated using PA Tools as more scientific discoveries about the population and environmental conditions most suitable for Zika are made. For example, recent evidence has shown that *A. aegypti* are able to overwinter as far north as Washington, D.C., and if this observation is validated in other northern locations the model can be adjusted to have a lower minimum temperature threshhold [11].

Conclusions

When future emerging infectious disease events occur, this process of identifying suitable environments based on historic epidemiological, entomological, and geographic data and then mapping areas with similar levels of risk can be rapidly deployed for use by response teams. Those maps can easily be updated as new environmental and risk factor data become available. The current map provides an enhanced global projection of where vector control initiatives may be most valuable for reducing the risk of Zika virus and other *Aedes*-borne infections.

Funding

No funding sources.

Competing interests

None declared.

Ethical approval

Not required.

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